An intercomparison of plasma turbulence at three comets: Grigg-Skjellerup, Giacobini-Zinner, and Halley

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Abstract. We examine and intercompare the LF plasma wave turbulence at three comets: Grigg-Skjellerup (GS), Giacobini - Zinner (GZ), and Halley (11). All three have power spectral peaks at the local ion cyclotron frequency (the pump wave) at $\sim 10^{-2}$ Hz, and a power-law fall-off at higher frequencies that suggest the development of turbulent cascades [*Acuna*, 1986]. The power laws for the three comets are approximately $f^{-1.9}$, $f^{-1.9}$ and $f^{-2.1}$, respectively. However, other than the similarities in the power spectra, wc find the magnetic field turbulence is considerably different at the three comets. Phase steepening is demonstrated to occur at the trailing edges of the GS waves. This is probably due to nonlinear steepening plus dispersion of the left-hand mode components. A coherency analysis of GZ turbulence indicates that it is primarily composed of right-handed mode components, i.e., the turbulence is "whistler-mode". This too can be explained by nonlinear steepening plus dispersion of the magnetosonic waves. At the level of GS and GZ turbulence development when the spacecraft measurements were made, classical three-wave processes, such as the decay or modulation instabilities do not appear to play important roles. It is most likely that the nonlinear steepening and dispersive time scales are more rapid than three-wave processes, and the latter had not had time to develop for the relatively "new" turbulence. The wave turbulence at I [alley is linearly polarized. The exact nature of this turbulence is still not well understood at this time. Several possibilities arc suggested, based on our preliminary analyses.

Introduction

Cometary waves provide us with our best opportunity in space plasma physics to study the development of plasma turbulence. In a steady flowing solar wind, instabilities associated with the pickup of freshly created ions will lead to electromagnetic wave power in a narrow frequency band, This frequency is the local ion cyclotron frequency in the cometary rest frame [*Tsurutani and Smith*, 1986]. Because spacecraft have had relatively low velocities with respect to comets during their flybys, the spacecraft magnetometer rest frame is essentially the cometary frame. Thus, waves measured at frequencies higher and lower [ban the pump frequency (presumably due to cascade and "inverse cascade" processes, respectively) can be easily studied, and the nature of the turbulence established. This situation does not exist for other waves in space plasmas. Variable Doppler shifts smear out the pump frequency, and the "daughter" and "granddaughter" waves are not as easily identified.

The purpose of this paper is to usc power spectra and coherency analyses to study the high frequency components of plasma waves and turbulence at comets Grigg-Skjellerup (GS), Giacobini-Zinner (GZ) and Halley (11) using high resolution magnetometer data from Giotto [*Neubauer et* al., 1986] and ICE [*Frandsen et al., 1978].*

Results

To determine the power spectra of the transverse waves at cornets, the mean-field direction over the analysis interval was determined first . The high resolution field data was rotated into the mean-fic]d coordinate system and the power spectra of the two transverse components were calculated and then summed. Figure 1 gives the power spectra of the transverse components of the three comets: GS, GZ and H. These were formed from analyses of magnetic field data at comparable locations just upstream of the bow shocks/waves.

There arc clearl y defined peaks in all three specks. They are located near the local water ion cyclotron frequency (1.7 x 10^{-2}, 6.6 x 10^{-3} and 7.4 x 10-3). For simplicity, we will say the peaks occur at -102 Hz. All three spectra have relatively smooth fall-offs at higher frequencies. Fitting these fall-offs to power-law spectra, the exponent in the f 'x dependence is 1.9 for GS, 1.9 for GZ and 2.1 for H. These values are similar to that expected for spectra developing towards Kolmogorov or Kraichnan turbulence (however, see *recent results* of Sridhar and Goldreich [1994] and Goldreich and Sridhar [1994] concerning Kraichnan turbulence).

If onc did not look further, onc might assume that the differences in power law arc simply indicative of different levels of evolution of the wave cascades. Assuming the initial spectrum consists of a sharply defined pump wave (plus background), the spectral fall-off should be quite steep. As the cascade process develops, more and more wave power will be placed at higher frequencies, lowering the steepness of the spectral slope. Thus, assuming this general scenario, one might deduce that the "turbulent" spectrum of the comet H is the least developed, and GS and GZ the most developed. This may be partially true, but we will show that the real case is not quite as simple as this.

In the classical cascade model, the waves through wave-wave interactions are expected to cascade to the proton cyclotron frequency, where they arc cyclotron damped (the wave sink). 1 lowever, in Figure 1, there is no inclination of such damping at this frequency (-160 mHz) in any of the three cometary wave spectra.

Onc also expects the generation of proton cyclotron waves by the pickup of cometary hydrogen. There arc no enhancements at -160 mHz in any of the spectra shown in Figure 1. This is a general observation for all the comets and is true for other intervals as well. At GZ there is an enhancement at -300 ml Iz, but this is almost at a frequency double the proton cyclotron frequency (-1 60 ml Iz). The small enhancement at -260 ml Iz at the GS spectrum is believed to be due to spin aliasing.

Proton cyclotron waves are, in general, not dctcctcd at comets [*Tsurutani, 1991; 1992]* except for limited, small-amplitude sporadic wave packets at Halley [*Mazelle and Neubauer, 1993].* It should be noted that similar wave packets have been detected in the absence of (obvious) comets [*Tsurutani et al.*, 1994], and thus the Mazelle and Neubauer (1993) association with a cometary ongin is not absolute. The important point here is that no major enhancement of wave power is present at the proton cyclotron frequency, certainly nothing comparable to the power at the H_2O group ion cyclotron frequency.

Figure 2 shows examples of wave forms for the three comets. Each is extremely different from the others. GS is characterized by sinusoidal, relatively noncompressive left-hand polarized waves [*Mazelle et d., 1994]*, GZ has phase-steepened and compressive magnetosonic (RH) waves led by large amplitude whistler packets, and H has waves with no obvious structure. For GS, GZ and H, the $|\Delta\vec{B}|/B_0$ transverse wave amplitudes are: -0.3, -1.0-2.0, and -0.5, $\theta_{kB} \leq 10°$, 10"- 50", and nearly isotropic, respectively. The beta values for the three comets arc: low (-0.1 - 0.2), -1.0 and 2.8. The last value comes from Coates et al. (1990). Previously, it had been assumed that the turbulence at H was the most developed duc to the larger scale size of the comet (due to higher neutral production rates), and thus had a longer time for the waves to develop and to "cascade".

There is an interesting new feature in the form of the GS waves shown in Figure 2. Previously reported waves were quasiperiodic and anhannonic [*Glassmeier and Neubauer, 1993; Neubauer et al., 1993]*. This is the typical case. The examples of the waves in Figure 2 were chosen to illustrate cases where the waves have phatse-steepened edges. These waves occur just prior to the bow shock/wave (on the outbound pass) and are therefore believed to be the most developed. The field is in a cometary centered system with the x-axis pointing towards the sun. The solar wind is propagating in essentially the - $\hat{x}$ direction.

The phase rotation of *one cycle of* the GS waves of Figure 2 is given in Figure 3. Radial spokes in the B_1 - B_2 hodogram indicate 20% increments of the interval of analysis (wave period). The hodogram starts with the triangle and ends with a circle. The minimum variance (MV) coordinate system is described in Smith and Tsurutani (1976). Note the amount of phase rotation is much higher at the end of the wave than at the beginning, indicating significant phase steepening on the trailing edge as noted in the wave forms in Figure 2.

During the GS encounter, the interplanetary magnetic field (IMF) is oriented approximately orthogonal to the solar wind flow direction, leading to the generation of parallel propagating left-hand polarized waves [*Neubauer et al.*, 1993; *Glassmeier and Neubauer, 1993]*. Beta is low and VA $\cong 1/3\, V_{SW}$. Because of the orthogonality of the field and the very high wave phase speed, the waves *are* propagating past the spacecraft with little or no Doppler shift. Thus, phase steepening which occurs last in time in the spacecraft frame, also occurs last in time in the plasma frame, relative to the wave propagation direction. Therefore, wc conclude that the phase steepening must be occurring at the trailing edges of the waves.

This feature is consistent with Shevchenko et al. (1994) results from recent Derivative Nonlinear Schrocdinger (DNLS) analyses. Some of the theoretical results give profiles very similar to those of the GS waves shown in the Figure (V. Shevchenko, personal communication, 1994). The steepening at the trailing edge can be understood by simple considerations. Due to nonlinear steepening ($|\Delta\vec{B}|/B_0$ - 0.3), higher frequency left-hand components arc created. Left-hand waves have decreasing phase velocity with increasing frequency (ω). At 6) ~Ω_{ci}, the ion cyclotron frequency, there is a cutoff and the wave phase velocity goes to zero [*Chen*, 198 1]. Thus the higher frequency wave components will physically trail the rest of the wave in time, leading to steepening which occurs at the trailing edge. It should be pointed out that this is opposite the case for magnetosonic (right-hand) waves where higher frequency right-hand waves have higher phase velocities. Magnetosonic wave phase steepening thus occurs at the leading edges.

Figure 4 shows the results of coherency analyses [e. g., see *Glassmeier et al.*, 1989] for waves at all three comets. The cross spectral density, coherence and ellipticity have been determined for the two transverse components of the field in the mean field coordinate system. The analysis has been done with 22 degrees of freedom. Positive (negative) ellipticity corresponds to left-hand (right-hand) polarization in the spacecraft frame of reference.

The GS waves arc coherent only at the pump frequency and slightly higher frequencies (7 x 10^{-3} to 2 x 10^{-2} Hz). This corresponds to the left-hand cyclotron pump waves plus the waves associated with phase steepening. The highest frequency components (> 3 x 10^{-2} Hz) do not have any notable coherency. In examining wave amplitudes in this frequency range, wc find that they arc consistent with being background solar wind turbulence. Thus, we conclude that the GS power spectrum is composed of two components of waves: left-hand turbulence near the pump and slightly higher frequencies, and unpolarized incoherent solar wind turbulence at the highest frequencies. There is no evidence of wave cascading at GS. here are only the previously discussed dispersive effects.

The GZ wave coherency is quite different. Near the pump frequency at -10-2 Hz, the coherency is relatively low, -0.3 to 0.6, and slightly left-handed (in the plasma frame). The lack of coherency between the two transverse components is consistent with the nonlinear development of the linearly polarized, compressive trailing portions of magnetosonic waves [*Tsurutani et al.*, 1987].

The highest frequency components at f >10^{-2} Hz are highly coherent (-0.8) and are left-hand polarized in the spacecraft frame. This is consistent with this component being anomalously Doppler shifted right-hand waves in the plasma frame. This whistler mode turbulence is most probably duc to dispersive effects [*Omidi* and *Winske*, 1990]. There is no evidence of significant three-wave cascade processes at GZ.

The H wave coherency is different again. At the pump frequency, the coherence is -0.5, about the same as for the GZ case. The polarization is indeterminate. At higher frequencies, the coherency is generally lower still. Increasing the number of degrees of freedom of analysis would result in smoothing the coherence and polarization. We conclude the H waves appear to be linearly polarized. At least three possible interpretations exist: 1) the turbulence could be an equal mixture of both right -and left-hand polarized waves propagating in the same direction, giving an average result of linear polarization, 2) the H waves could have evolved nonlinearly to a point where the waves at 10^{-2} Hz arc linearly polarized (such as those found in the trailing portion of the GZ magnetosonic waves), or 3) the spectrum is indeed fully turbulent. At this time, none of these possibilities have been ruled out. It will take further effort to analyze the detailed small scale wave structures and to also search for "daughter" and "granddaughter" waves to determine which one (if any) is the correct mechanism. This is, however', beyond the scope of this present paper.

Conclusions

A comparison of waves at three comets has indicated that the turbulence of each is quite different from the others. GS is a superposition of left-hand waves (near the pump) plus solar wind background turbulence (at higher frequencies). GZ is composed of linearly polarized turbulence near the pump frequency and dispersive right-hand turbulence at higher frequencies, and H is linearly polarized turbulence. The biggest mystery at this time is the 1 I turbulence. From the orientation of the IMF relative to the solar wind velocity of the H encounter (typically a Parker spiral angle: Neubauer et al., 1986), onc would expect magnetosonic mode generation [*Thorne and Tsurutani,* 1987; *Brinca*, 1991; Gary, 1991]. However, from an initial inspection of the wave forms, whistler packets were not observed [*Glassmeier et al.,* 1987]. This is not presently understood. Onc possibility is that plasma conditions might play an important role in this. With higher β (than the GZ case), whistlers could be readily damped, leaving the linearly polarized waves remaining. This possibility is currently being studied. Another possibility is that because the Halley scale is so large, the waves have had much longer to develop and are, as a consequence, fully turbulent. Small scale H waves are currently being investigated to determine which of these possibilities is the correct one.

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Figure Captions

Figure 1. **Power** spectra of the transverse components of the magnetic field at three comets.

Figure 2. Wave forms of LF waves at three comets.

Figure 3. The magnetic field of a GS wave in minimum variance (MV) coordinates. The B_1 - B_2 hodogram at the lower left illustrates the magnitude of phase steepening. The time resolution is ones. The eigenvalue ratios are 378:229:1.

Figure 4. The magnetic energy density, coherency and ellipticity of waves at three comets; ± values of ellipticity corresponds to left-hand and right-hand Polarization.

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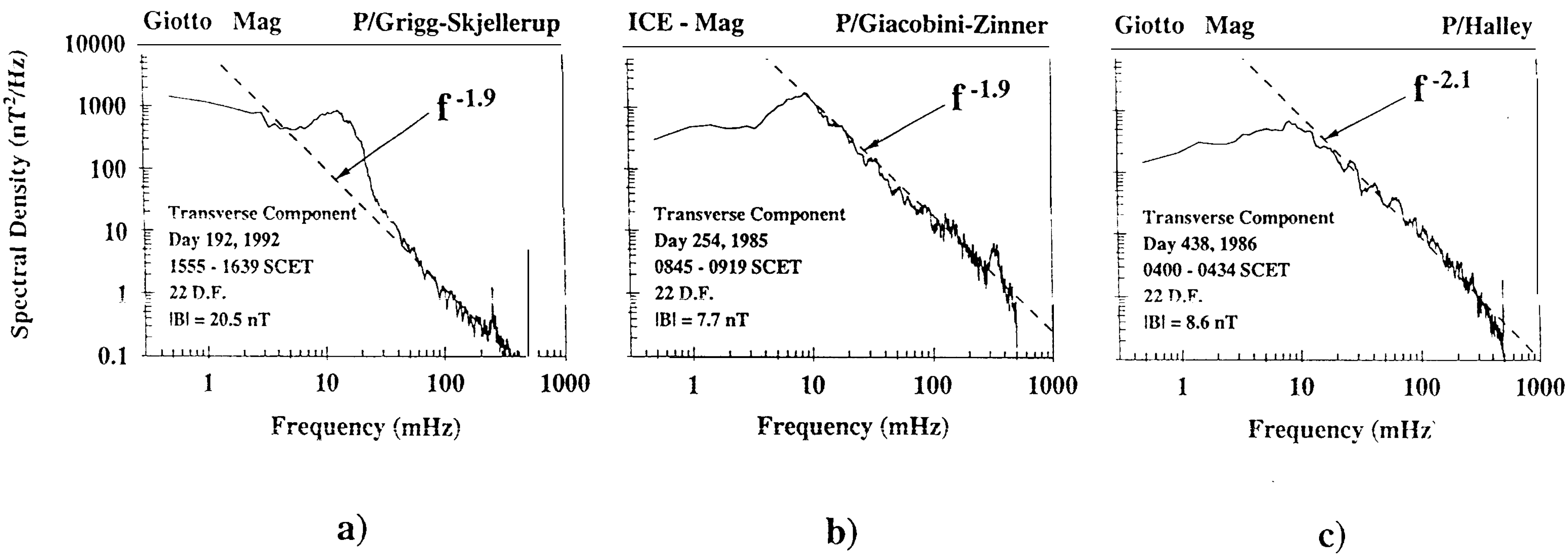
Giotto Mag
P/Grigg-Skjellerup
Spectral Density (nT^2/Hz)
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1000
100
10
1
0.1
$f^{-1.9}$
Transverse Component
Day 192, 1992
1555 - 1639 SCET
22 D.F.
|B| = 20.5 nT
1
10
100
1000
Frequency (mHz)
a)
ICE - Mag
P/Giacobini-Zinner
$f^{-1.9}$
Transverse Component
Day 254, 1985
0845 - 0919 SCET
22 D.F.
|B| = 7.7 nT
1
10
100
1000
Frequency (mHz)
b)
Giotto Mag
P/Halley
$f^{-2.1}$
Transverse Component
Day 438, 1986
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22 D.F.
|B| = 8.6 nT
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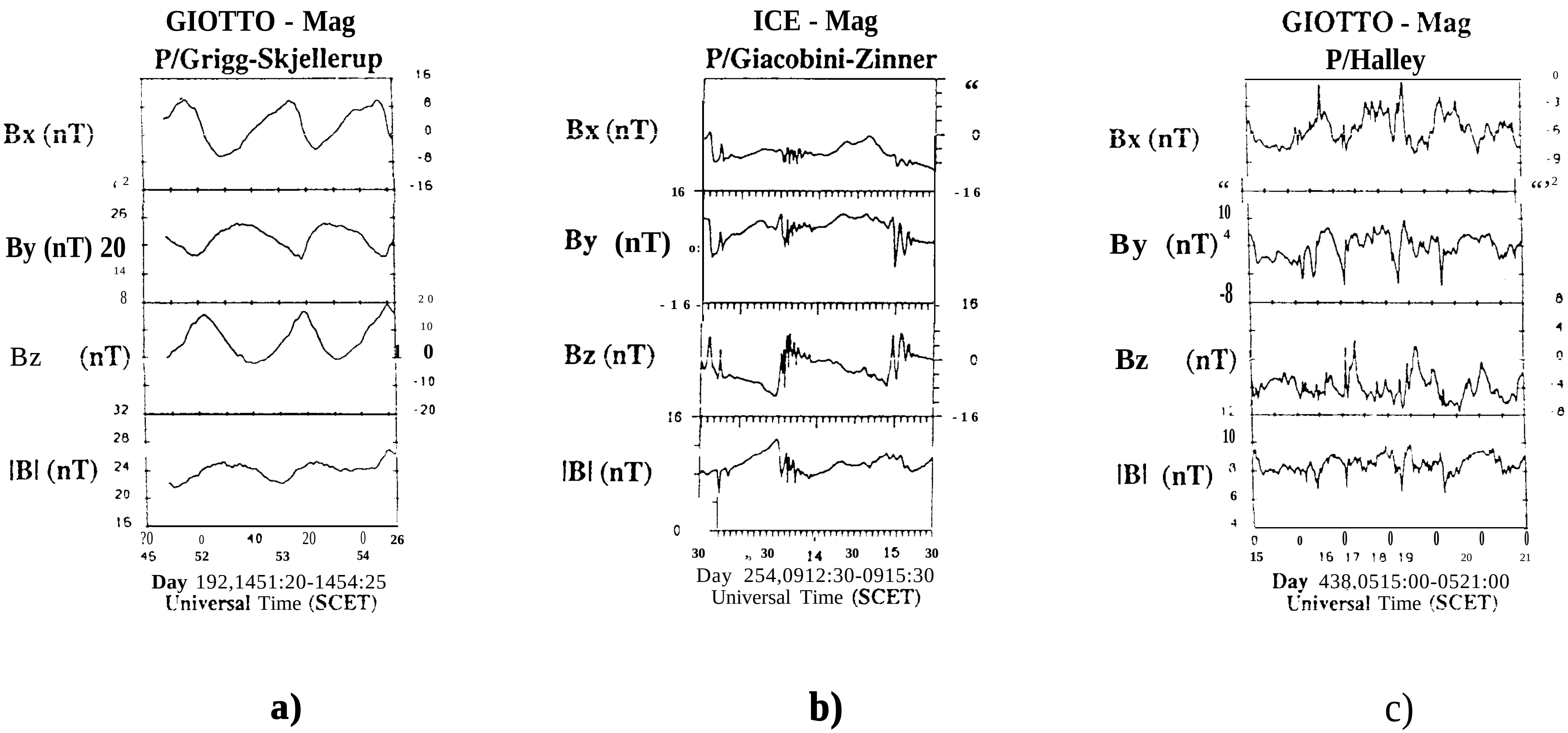
10
100
1000
Frequency (mHz)
c)

Figure 1.


GIOTTO - Mag
P/Grigg-Skjellerup
Bx (nT)
By (nT)
Bz (nT)
|B| (nT)
Day 192,1451:20-1454:25
Universal Time (SCET)
a)
ICE - Mag
P/Giacobini-Zinner
Bx (nT)
By (nT)
Bz (nT)
|B| (nT)
Day 254,0912:30-0915:30
Universal Time (SCET)
b)
GIOTTO - Mag
P/Halley
Bx (nT)
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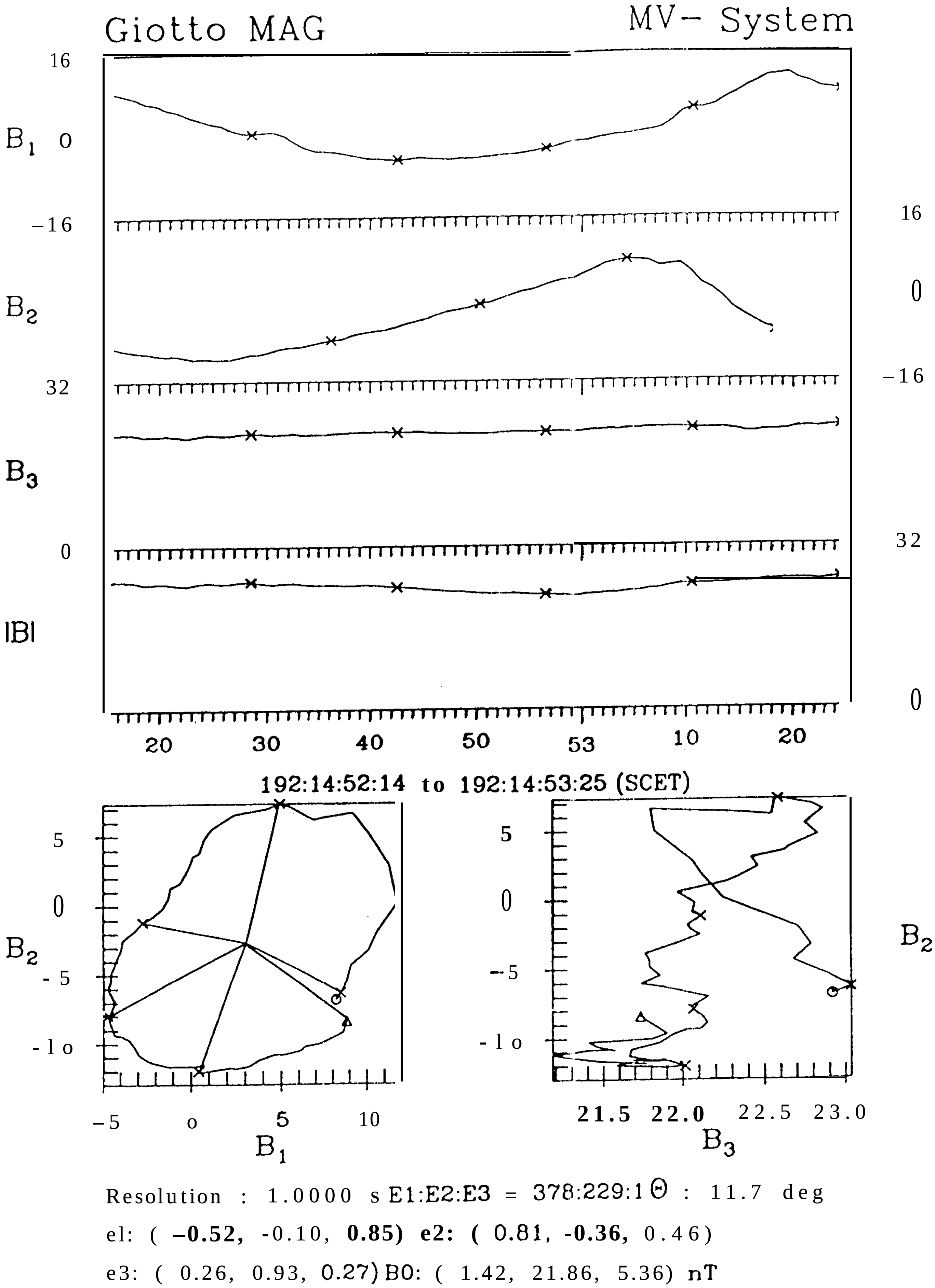
Universal Time (SCET)
c)

Figure 2.


Giotto MAG
MV- System
B1
B2
B3
|B|
16
0
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32
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20 30 40 50 53 10 20
192:14:52:14 to 192:14:53:25 (SCET)
5
0
-5
-10
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B1
B2
21.5 22.0 22.5 23.0
B3
Resolution : 1.0000 s E1:E2:E3 = 378:229:1 Θ : 11.7 deg
el: (-0.52, -0.10, 0.85) e2: (0.81, -0.36, 0.46)
e3: (0.26, 0.93, 0.27) B0: (1.42, 21.86, 5.36) nT

Figure 3.

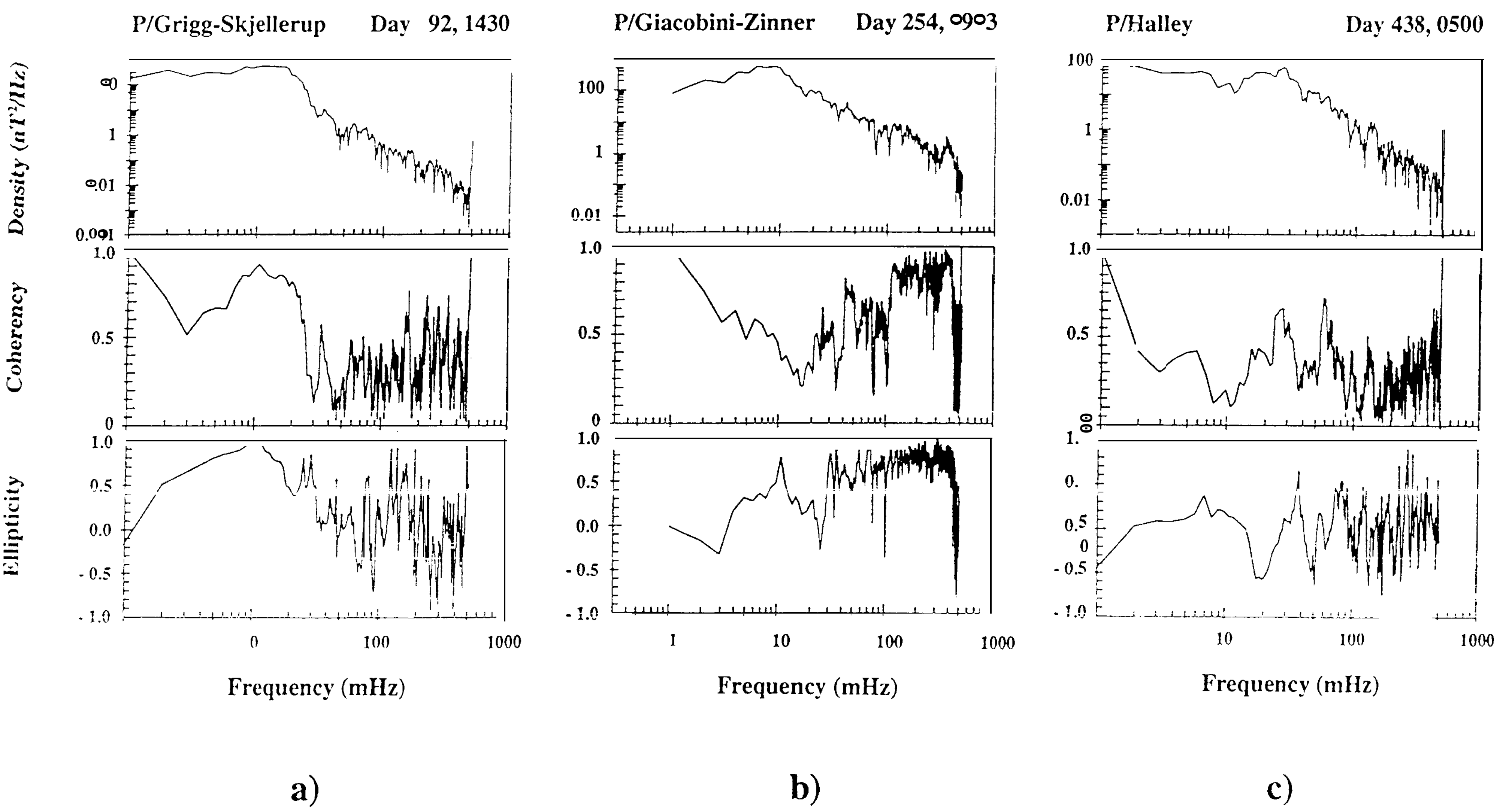
P/Grigg-Skjellerup
Day 92, 1430
P/Giacobini-Zinner
Day 254, 0903
P/Halley
Day 438, 0500
Density (nT²/Hz)
Coherency
Ellipticity
Frequency (mHz)
Frequency (mHz)
Frequency (mHz)
a)
b)
c)

Figure 4.